EXPERIMENTAL INVESTIGATION OF NOZZLE/PLUME AERODYNAMICS AT HYPERSONIC SPEEDS

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I. SUMMARY

An extensive program to improve the operation of the Ames 16 Inch Shock Tunnel was carried out. This included reduction of driver slosh wave amplitudes and detonation risk by the use of premixed He/O_2 gas, longer wait times between the last gas load and driver gas ignition, an improved gas loading sequence, the use of four instead of one ignition wires and the use of lower ignition wire voltages. Successful operation of the tunnel at pressures of 2000-6000 psi and enthalpies up to 12,000 J/gm was achieved. A new diaphragm breaking technique, self break on the driver combustion pressure rise, was tested and found to produce clean breaks over the full pressure range of the tunnel. Improvements were made to the driver gas loading manifold and a preliminary design was made of a gas mixing system which mixes all three gases on the fly just before injection into the driver.

The driver gas free test time was estimated by various methods to be ~5 msec for 10,000 J/gm enthalpies. A spark

spectroscopy system to allow more precise measurements of the test time has been designed and constructed. Fifty-five instrumentation amplifiers with a gain of 100 and a 3 db roll-off frequency of 70 kHz have been constructed and have proven very satisfactory.

Tests have been performed on a wedge model with hydrogen injection. The model is instrumented with surface pressure and heat flux gauges, pitot probes, accelerometers and pressure transducers to monitor the hydrogen fuel flow. Also, holographic interferograms were taken in the spanwise direction. Test were made at driven tube reservoir pressures of 4000 and 6000 psi and reservoir enthalpies of 10,000 and 12,000 J/gm. Tare runs (air flow, no injection), mixing runs (nitrogen flow, H_2 injection) and combustion runs (air flow, H_2 injection) were made. The data has been only partially reduced and analyzed to date.

A new test section has been installed and a new rake to calibrate the test section is being constructed. Calibration will take take place in 4-55/92. A scramjet combustor model is being constructed at GASL and combustor tests will begin in 6/92. D. W. Bogdanoff is the chief designer of the

hydrogen fuel injection system for the combustor model.

II. DETAILED DISCUSSION

A. Improvement in operation of facility

In this contract period an extensive program for improvement of the operation of the Ames 16 Inch Shock Tunnel has been carried out. The main goals have been the following:

- Operation of the tunnel at higher pressures and enthalpies
- Reduction of the amplitude of driver slosh waves
- Reduction of detonation risk
- Reduction of test gas contamination
- Reduction in the time required to turn the tunnel around
- Reduction of damage to components during tunnel operation

The after burn driver slosh waves are believed to be due to poorly mixed driver gas and the voltage asymmetry of the wire ignition system. The conditions that produce large amplitude slosh waves are also very likely to produce detonations under unfavorable conditions. Several steps have been taken to improve the gas mixing. First, premixed He/O_2 and H_2 are now used, instead of three separate gases. The

composition of the mixed gas is continually monitored during the loading process with a thermal conductivity gauge. This ensures that two of the three gases are properly mixed and avoids the introduction of heavy, slowly diffusing pure oxygen into the tube. Earlier in the test program, the wait time from the loading of the last gas until driver gas ignition was only 15-20 min. Thus, relatively little time was available for gravitational equilibration and diffusion mixing of the driver gas in the vertical direction. Longer wait times, up to 24 hr, were tested and shown to produce significant reductions in the driver slosh waves. Such long times are not acceptable for fast tunnel turn around. However, the wait times were increased to 90-150 min, which had been shown to still produce significant reduction in the driver slosh wave amplitudes. These were the maximum wait times which could be used without adversely effecting the tunnel turn around time. Also, an improved gas loading order, H_2 followed by the He/O_2 gas mixture, has been instituted. This also produced significant reduction in the slosh wave amplitude.

The use of three and four, rather than one ignition

wires was tested. The use of more ignition wires reduces the burn time substantially, thus reducing the time available for slosh waves and detonations to build up. We now are using four wires regularly. Reduction in the wire voltage, while maintaining the wire final temperature has been tested and found to reduce the slosh wave amplitude. (Such reductions can be accomplished by increasing the capacitance of the capacitor bank used to heat the wire(s) or by using thinner wires.) The capacitor bank voltage has been reduced from 18.5 kV to 14.0 kV. Several techniques were tried which were found not to improve matters or to make things worse. These were:

- Thermal stirring of driver gas before ignition
- Reversal of wire polarity
- Use of Dannenberg and Stewart's highly diluted gas mixture.

Accordingly, these techniques were abandoned.

Controlled, successful operation of the tunnel at pressures of 2000-6000 psi was achieved. By operating the tunnel in the non-tailored, equilibrium interface mode reservoir enthalpies up to 12,000 J/gm have been achieved. This corre-

sponds to flight in the stratosphere at Mach 16.

Breaking of the diaphragm using the lance is limited to 1000 psi operation. High explosive jet cord can be used to break the diaphragm over the full pressure range of the tunnel, but severely contaminates the flow. A variant of the double diaphragm technique was tested but failed due to detonation in the interdiaphragm space followed by detonation in the driver. Self-break of the diaphragm on driver pressure rise was tested and found to produce clean breaks over the full pressure range of the tunnel. This is now the diaphragm break method being used. The variation of the diaphragm break pressure using this technique was found to be $\pm 7.5\%$.

The orifices of the early driver gas injection manifolds burned out fairly easily. New manifolds with a much more robust hole design have been constructed. In addition, short sections of manifold with screw-in, replacable orifices will be tested in the 1992 tunnel entry. A more robust manifold restraint system has been constructed and will also be tested in the 1992 tunnel entry. A preliminary design has been made of a gas mixing system which mixes all three gases

on the fly before injection into the driver. Such a system would likely produce large reductions in slosh wave amplitude and detonation risk and would eliminate the manifold and all work and expense associated with it and would eliminate the wait time between loading the driver gas and ignition. This system may be implemented in the fall or winter of 1992.

B. Driver gas free test time

Test section static pressure measurements suggest a test time of 8 or 9 millseconds before heavy (greater than 15%) driver gas contamination under "hot" (10,500 J/gm) operating conditions. Correlations from the literature suggest driver gas free test times of 5.5 and 13 milliseconds for hot and "medium" (4,700 J/gm) operating conditions, respectively. For the "hot" conditions, laser based OH temperature measurements suggest a driver gas free test time of $\sim$5 msec. A spark gap has been constructed so that spectroscopic measurements of driver gas helium arrival time can be made. The 584.7 nm line of helium will most likely be used for these measurements. It is planned to implement this system in the fall or winter of 1992.

C. Instrumentation amplifiers

We have developed an in-house amplifier based on single inexpensive chip. Fifty-five of these amplifiers have been built. Most of the amplifiers have a gain of 100. The 3 db roll-off frequency of these amplifiers is 70 kHz. The amplifiers have given excellent service in the wedge model tests (see Secs. D-F).

D. Wedge model - description

The chord and span of the wedge model are 38 cm and 46 cm, respectively. The model has five 30^o 0.305 cm diameter hydrogen injection ports arranged in a spanwise row at about mid chord. The model can be pitched over a angle of attack range of 0^o to 22^o. The model instrumentation includes 12 static pressure transducers (Kulites) and 14 heat transfer gauges (10 coaxial thermocouples, 2 platinum thin film gauges and 2 thin skin slug calorimeters) on the model surface. Seventy precent of the surface gauges are downstream of the injectors. Two pitot probes are located at the model leading edge and a seven head pitot rake is located at the trailing edge. Four accelerometers measure accelerations in

the x, y and z directions. Laser holographic interferograms can be taken in the spanwise direction.

The hydrogen fuel system can inject room temperature hydrogen at plenum pressures up to 27 atm. Two pressure transducers measure the hydrogen plenum pressure and the mass flow is measured using a venturi. The venturi upstream pressure and pressure difference are measured with pressure transducers. The venturi was calibrated with a sonic orifice using nitrogen and helium flows.

E. Wedge model - tests run

Three types of tests were run. Tare runs used air as the driven tube gas with no hydrogen injection. Mixing runs used nitrogen driven tube gas with hydrogen injection. Finally, combustion runs used air driven tube gas with hydrogen injection. Eleven tests were made in the series, including one test with detonation in the driver, leaving ten good test runs. One preliminary tare run was made at 136 atm driver pressure and Mach 14 driven tube reservoir enthalpy. Seven runs were made at 272 atm driver pressure. Six of the runs were at Mach 14 enthalpy, comprising one tare run, two mixing runs and three combustion runs. One of the three combus-

tion runs was made at twice the hydrogen mass flow rate of the other two runs. (We will refer to this run as the "high-q" run.) The last 272 atm driver pressure run was made at Mach 16+ enthalpy. Two runs, a mixing and a combustion run, were made at 408 atm driver pressure and Mach 16 enthalpy.

F. Wedge model - preliminary results

The data has only been partially reduced at this time; hence the following results are preliminary. Very little of the 408 atm driver data has been reduced. Hence, the discussion below deals with 272 atm driver pressure data only. Overall, data acquistion was very good; about 90% of the data which should have been collected was, in fact, collected. The in-house built amplifiers performed very well, as discussed above.

The platinum thin film heat transfer gauges proved very fragile in our environment. After the first two tests, both gauges had been destroyed, showing infinite resistance. One slug calorimeter failed on the next to last test; the remaining calorimeter remained operational for the full test series. For each run typically up to two coaxial thermocouples would initially give good data and then open up to

infinite resistance. However, the coaxial thermocouples could be restored to service by abrasion and burnishing. At the end of the wedge test program, all coaxial thermocouples were still operational.

For the tare runs the static pressures were nearly identical over the whole wedge surface, as expected. With hydrogen injection, pressure increases due to the hydrogen plume shocks could be seen. These pressure increases were larger for the high-q run. The aft pitot rake showed the wedge shock location and the reduction in dynamic pressure due to the hydrogen injection plume. The reduced dynamic pressure area was larger for the high-q run. The wedge shock moved further away from the wedge surface with injection, presumably since the plume shock merged with the wedge shock and strengthened it.

The heat flux data for the tare run showed greatly increased heat flux just aft of the injection holes, presumably as result of the holes tripping the boundary layer. For the gauges just aft of the injectors, no effect could be seen midway between the injectors, However, gauges midway between the injectors and just upstream of the trailing

also showed this increse, indicating that the tripped region was spreading laterally. With injection, gauges on the injector centerlines showed an increase of heat flux (compared to that with tare runs) just upstream of the injectors, likely a result of plume shock compression and a reduction of heat transfer downstream of the injectors, likely a result of hydrogen film cooling. The increase upstream of the injectors was larger for the high-q run. With injection, for the gauges midway between the injectors, the heat flux increased downstream of the injectors, likely a result of plume shock compression, except at the most downstream station, where the heat flux decreased, likely a result of progressive spanwise spreading of the hydrogen film cooling effect.

The laser holographic interferograms showed the wedge shock, the plumes of hydrogen up to the pitot rake and the plume shock merging with the wedge shock near the trailing edge of the model. The reduction of the data is continuing and a paper giving the results will be presented at the 28th AIAA/SAE/ASME/ASEE Joint Propulsion Conference in Nashville, TN, July 6-8, 1992.

G. New test section

A new test section, built by Fluidyne, has been installed. This test section will allow greatly improved physical and optical access to the model. Critical input for the test section design was provided by D. W. Bogdanoff in the following aresa: expected model loads, model mounting system, instrumentation feedthroughs and window design.

H. Rake to calibrate new test section

A new rake is being constructed at Fluidyne to allow calibration of the new test section. The rake will have ~36 heads to measure pitot and static pressure and stagnation point heat flux. This rake will be much more versatile than the earlier fixed rake. It will be able to traverse in the the x and z directions and to rotate. It also has 3 times as many heads as the earlier rake and can measure heat flux, which the earlier rake could not. Considerable input was provided by D. W. Bogdanoff in the design of the rake. This included calculation of forces on the rake, designs for all three types of heads, shield designs for the pitot pressure heads and recommendations for instrumentation feedthroughs

and wiring and amplifier configurations. Calibration of the new test section using this rake will take place in 4-5/92.

I. Combustor model

A scramjet combustor model is being fabricated for Pratt and Whitney and Rocketdyne by GASL. Considerable design input for this model was provided by D. W. Bogdanoff. This included calculation of forces on the model and recommendations regarding selection of transducers, location of pitot rakes and configurations of instrumentation feedthroughs, wiring and amplifiers.

J. Hydrogen fuel system for combustor model

D. W. Bogdanoff is the chief designer of the hydrogen fuel system for the combustor model. Input has been received from Ames, Pratt and Whitney, Rocketdyne and GASL personnel. Two systems are required, one for the cowl side and one for the body side of the model. Very high hydrogen mass flow rates, up to 1+ kg/sec (total) must be delivered. The system will initially be based on a 10 msec, 750 psi valve made by Marotta. (At a later time, a considerably more expensive 10 msec, 3000 psi valve made by Flodyne may be used.)

An initial system configuration was made based on two 90 ft long Ludweig tubes. The final selected configuration is based on two spherical reservoir vessels with volumes of $\sim$1 ft^3. Provisions have been made in the design for evacuation, loading and flushing with He or N_2. The necessary safety systems, including burst discs, adequate venting options and fail-safe valve arrangements, have been included. Another safety requirement is that the total amount of hydrogen in the system is limited to 400 scf. Remote pressure measuring transmitters have been provided in the initial hydrogen storage reservoirs and the two spheres. Special feedthroughs for the tunnel vacuum wall and special fittings for use with the Marotta valves have been designed. The design is about 90% complete and procurement and fabrication of components will start in 3/92.